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Waste energy recovery in seawater reverse osmosis desalination plants. Part 1: Review

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ABSTRACT

The reduction of energy consumption constitutes one of the major thrust areas of research in seawater reverse osmosis (SWRO) desalination plants. The cost of energy in the SWRO process is usually about 30–50% of the total production cost of water and can be as much as 75% of the operating cost, depending on the cost of electricity. Thus, energy forms the major contributing factor in determining the water production cost. Hence reducing the energy consumption, which is mainly due to wastage of energy in high-pressure brine, is a main goal of desalination industries.

Energy recovery devices are employed in seawater reverse osmosis (SWRO) desalination plants to recover the high pressure energy from the membrane exhaust stream (60:80 bar) and return it back to the process. Because of this high exhaust (concentrate) pressures at high flow rates, the membrane exhaust stream contains a considerable amount of energy to be recovered. Recently, isobaric energy recovery devices and turbochargers have been used for SWRO performance improvement. These devices are intended to provide greater energy-savings and greater capacity than was previously achievable.

This paper gives a comprehensive overview of the available energy recovery devices (ERDs) that can be used in seawater reverse osmosis (SWRO) systems, with emphasis on technologies and economics. A comparative study between different ERDs technologies as well as performance and economics has been done. These include turbines, turbochargers and isobaric devices at different design configurations. Special attention is given to the use of ERDs in seawater RO desalination. Finally, some general guidelines are given for selection of ERDs and parameters that need to be considered (specific power consumption kWh/m^3, energy saving%, and the corresponding cost saving).

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1. Introduction

1.1. Reverse osmosis (RO) a-reverse osmosis process

Following are some definitions that will help in understanding what a reverse osmosis process is and how it works with the aid of (Fig. 1a and b) [1]:

- *Osmosis* process is the tendency of water to flow through a semi-permeable membrane into a more concentrated solution as shown in Fig. 1a.
- *Reverse osmosis* process is the passage of water out of a solution when a pressure greater than the osmotic pressure is applied on the solution side of a semi-permeable membrane, Fig. 1b.
- *Semi-permeable membrane*: a membrane that allows water to pass through but rejects most ions and molecules.
- *Osmotic pressure*: the pressure needed to stop the flow of water through a semi-permeable membrane.
- *Reverse osmosis membrane* ([illegible]): RO membranes act as a barrier to all dissolved salts, inorganic molecules, and molecules with a molecular weight greater than approximately 100. Rejection of dissolved salts is typically [illegible] 99%. Trans-membrane pressures for RO typically range from [illegible] to 800 psi for seawater.

A huge amount of energy is expended to achieve the required pressure levels for the process, which is then rendered useless after the process ends. By this, it is implied that the energy used to raise the pressure of the seawater feed goes to waste when the remaining brine, which is also at high-pressure, has to be eliminated as a waste.

A way had to be sought that would enable the reuse of the pressurized brine and would thus help in reuse of energy. The disposal of highly pressurized brine proved to be a major drawback of the system and led to an urgent need for the formulation of an efficient "energy recovery" process.

1.2. Simple reverse osmosis system

Reverse osmosis is a form of filtration, in which the filter is a semi-permeable membrane that allows water to pass through, but not salt. When a membrane of this type has saltwater on one side and freshwater on the other, and in the absence of applied mechanical pressure, water will flow through the membrane towards the saltwater side, evening out the concentrations and reducing the quantity of freshwater. This is the natural process of osmosis, and is widely employed in the cells of all living species. In desalination, of course, the aim is to *increase* the quantity of freshwater and so a pump is employed to make the flow reverse, hence the name: reverse osmosis. Osmosis is a surprisingly powerful phenomenon; the osmotic pressure of typical seawater is around 26 bar, and this is the pressure that the pump must overcome in order to reverse the flow (26 bar also equates to the theoretical minimum energy consumption of 0.7 kW h/m^3, mentioned earlier). In practice, a significantly higher pressure is used, typically 50–80 bar, in order to achieve a generous flow of freshwater, which is the *product*, also known as the *permeate*. Of course, as freshwater passes through the membrane, the remaining saltwater becomes more concentrated and, for the process to continue, this *concentrate*, also known as the *brine*, must be continuously replaced by new feed water. To achieve this, the feed water is pumped *across* the membrane as well as through it; hence, RO is a *cross-flow* filtration process as depicted in Fig. 2.

The ratio of product flow to that of the feed is known as the *recovery ratio*. With seawater RO, a recovery ratio of 30% is typical, meaning that the remaining 70% appears as concentrate, which is returned to the sea. However, this concentrate comes out of the reverse osmosis module at a pressure only slightly below that of the feed, meaning that it contains roughly two-thirds of the total hydraulic power originally supplied by the pump.

In large RO systems, this energy is usually recovered by way of a Pelton turbine and returned to the shaft of the main pump, allowing the motor size to be roughly halved and dramatically improving the overall system efficiency. This is known as *brine-stream energy recovery*. In small RO systems, brine-stream energy recovery is often omitted, which reduces capital costs but adds considerably to running costs (energy). Reverse osmosis is a widely scalable technology: the membranes found in small systems used on pleasure yachts to produce a few litres per day are virtually identical to those used in large municipal plants producing thousands of cubic metres per day. The balance of plant (pumps, etc.) is, however, widely different and this usually leads to lower energy efficiencies in smaller systems, particularly when brine-stream energy recovery is neglected.

Nomenclature

BWRO	Brackish water reverse osmosis
c	electric cost, $/m^3
Cap Ex	capital expense
DC	direct capital cost
dP	pressure drop, bar
HP	high pressure
ERDs	energy recovery devices
HHP	high pressure pump
K	specific chemicals cost, $/m^3
L	specific cost of operating labor, $/m^3
LP	low pressure
m	plant capacity, m^3/day
NPSH	net positive suction head
Op Ex	operating expense
PX	pressure exchanger
R	membrane recovery, %
SI	salinity increase
SWRO	seawater reverse osmosis
TURBO	turbocharger
VFD	variable frequency drive
W	specific consumption of electric power, KW h/m^3

Subscripts

BP	booster pump
BPI	booster pump inlet
CP	circulation pump
CPM	circulation pump motor
E	discharge or exit flow
F	Feed
HP	high pressure
P	permeate
T	turbine

Greek symbols

η	efficiency

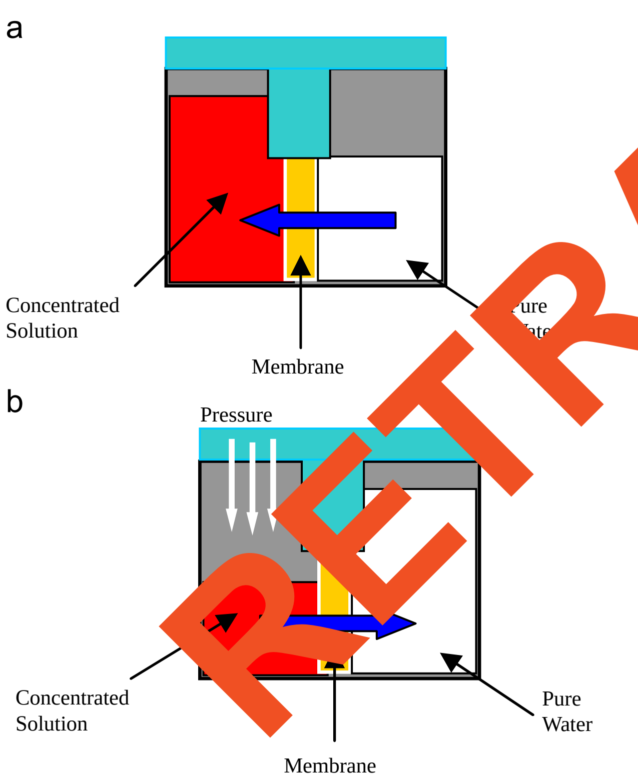

Fig. 1. (a) Osmosis process conceptual illustration [1] and (b) Reverse osmosis conceptual illustration [1].

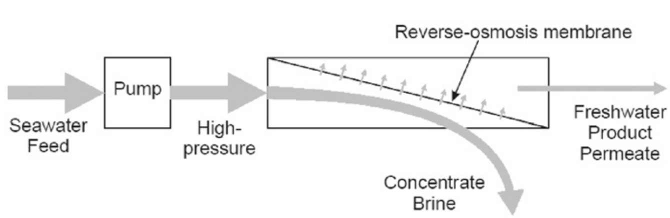

Fig. 2. Schematic of a simple reverse osmosis (RO) system [2–4].

1.3. Reverse osmosis (RO) technology and its development

Here, the RO technology and its development will be discussed in a little more detail. The early development of reverse osmosis is described by [illegible]rten et al. [5] and the mainstream industrial application of the technology is discussed by Byrne (1995). Also, several of the membrane manufacturers provide comprehensive handbooks [5].

An RO membrane may be thought of, initially at least, as an extremely fine sieve that allows water to pass through, but not salt. However, microscopic study of an RO membrane reveals that it is not really a sieve, but rather that the water diffuses through the membrane while salt cannot. Such membranes are described as semi-permeable and were developed for the purpose of desalination during the 1950s and 1960s. RO desalination was introduced commercially during the 1970s and now represents over 51% of installed desalination capacity worldwide [2]

1.3.1. Membrane materials

The early commercial membranes were cellulose acetate, but since the 1980s, the desalination market has been dominated by thin-film composite membranes, comprising a thin semi-permeable polyamide (nylon) layer supported on a thicker porous polysulphone backing. The physical strength of the membrane and its support structure are critical for it to withstand the high pressures required in desalination.

1.3.2. Hollow-fiber permeators

The first commercial desalination membranes were made in the form of hollow fibers. The saltwater is pumped in at one end of the fiber, freshwater emerges through the membrane wall of the fiber, and the concentrate comes out of the other end. A large number of fibers are assembled into a bundle to form a *permeator*. Hollow-fiber RO permeators are still manufactured, but the market is now dominated by the *spiral-wound* arrangement.

1.3.3. Spiral-wound membrane elements

In the spiral-wound arrangement, the membrane is in sheet-form and has the feel of stiff coated paper. Two sheets are assembled to form a sandwich with a mesh spacer layer in the middle. The

pressurized feed water will be on the outside and the freshwater will pass through the membrane into the spacer layer. The spacer layer is sealed on three sides and the fourth is joined to a freshwater collection tube.

In order to save space and cost in pressure vessels, the membrane sandwich is rolled onto the tube as illustrated in Fig. 3 to form a membrane *element*. A second mesh spacer layer is required to carry the feed water, and, in practice, two or four sandwiches are wound onto each collection tube, which reduces the distance that the freshwater has to travel round the spiral into the tube. The feed water is pumped in at one end of the spiral element and the concentrate appears at the other.

RO elements are usually 20, 40 or 60 in. long and 2½, 4 or 8 in. diameter, the use of inches underlining the fact that most RO elements are manufactured, or at least designed, in the US. For use, the membrane elements are loaded into tubular pressure vessels. Typical pressure vessels hold between one and seven 40-in. elements and can be connected in series and parallel to achieve the desired plant capacity. Large-scale RO plants have hundreds of pressure vessels.

1.3.4. Fouling, scaling and membrane life

A major consideration in the design and operation of any RO system is the avoidance, or at least management, of fouling and scaling of the membranes, since this determines the frequency of required membrane cleaning and replacement. The rate of membrane fouling and scaling is very dependent on feed-water quality and pre-treatment, and the membrane manufacturers' handbooks all devote substantial sections to these topics.

Scaling, in the context of RO, refers to the precipitation of sparingly soluble salts on the membrane surface when they become too concentrated. Scaling is commonly a limiting factor in systems using brackish feed water with high recovery ratios. In systems with seawater, the osmotic pressure tends to limit the recovery ratio and scaling is rarely a major problem. With seawater, the main consideration is biological fouling, caused by bacteria.

Pre-treatment often includes the addition of chemicals to the feed water that control fouling and scaling of the membranes. However, there is a trend within the industry to reduce the use of chemical additives and to pay more attention to the design of the feed water intake, so as to obtain cleaner water in the first place [5].

1.3.5. Temperature effect

The rate of diffusion of water through an RO membrane, and hence the product flow, is very dependent on the driving pressure, but temperature is also a very significant factor. An increase in feed temperature of 4 °C will cause the product flow to increase by about 10% [5], *assuming* that other factors are kept constant. But, in systems employing efficient brine-stream energy recovery, the overall effect of temperature is greatly reduced.

1.3.6. High-rejection and High-flow membranes

RO membrane manufacturers typically offer seawater RO membrane elements in two grades: *high-rejection* elements provide low-concentration product, while *high-flow* elements provide a greater volume flow of product, but at slightly increased concentration. Even with high-flow elements, product concentration is usually perfectly acceptable in normal seawater desalination applications. The costs for the two grades are similar [5].

1.3.7. The key elements of RO desalination plants

Reverse osmosis (RO) is a membrane separation process that recovers water from a saline solution pressurized to a point greater than the osmotic pressure of the solution (Fig. 4). In essence, membrane filters hold back the salt ions from the pressurized solution, allowing only the water to pass. RO membranes are sensitive to pH, oxidizers, a wide range of organics, algae, bacteria, depositions of particulates and fouling. Therefore, pre-treatment of the feed water is an important process step and can have a significant impact on the cost and energy consumption of RO, especially since all the feed water, even the amount that will eventually be discharged, must be pretreated before being passed to the membrane. Recently, micro-, ultra- and nano-filtration has been proposed as an alternative to the chemical pretreatment of raw water in order to avoid contamination of the brine water by the additives in the surrounding of the plants. RO post-treatment includes removing dissolved gases (CO_2), and stabilizing the pH via the addition of Ca or Na salts, and the removal of dangerous substances from the brine.

Pressurizing the saline water accounts for most of the energy consumed by RO. Since the osmotic pressure, and hence the pressure required to perform the separation is directly related to the salt concentration, RO is often the method of choice for brackish water, where only low to intermediate pressures are required. The operating pressure for brackish water systems ranges from 10 to 15 bar and for seawater systems from 50 to 80 bar (the osmotic pressure of seawater with a salinity of 35 g/kg is about 25 bar) [2].

The five key elements of a desalination system for either brackish water or seawater desalination are as follows [1–4]:

1. Intakes are the structures used to extract source water and convey it to the process system.
2. Pretreatment is a removal of suspended solids and control of biological growth, to prepare the source water for further processing.
3. Desalination is the process that removes dissolved solids, primarily salts and other inorganic constituents, from a water source.
4. Post-treatment is the addition of chemicals to the product water to prevent corrosion of downstream infrastructure piping.
5. Concentrate management is the handling and disposal or reuse of waste residuals from the desalination system.

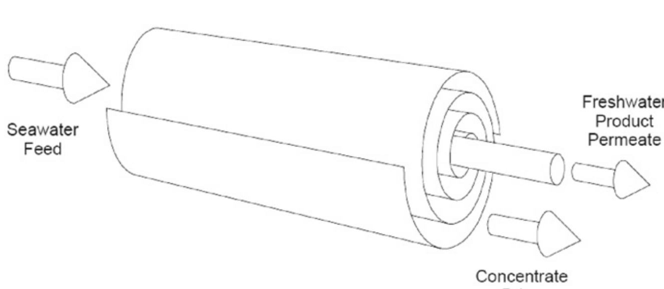

Fig. 3. Spiral-wound RO element [4].

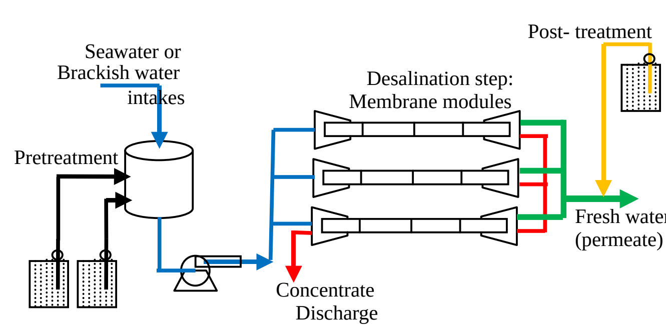

Fig. 4. The key elements of reverse osmosis plant [2].

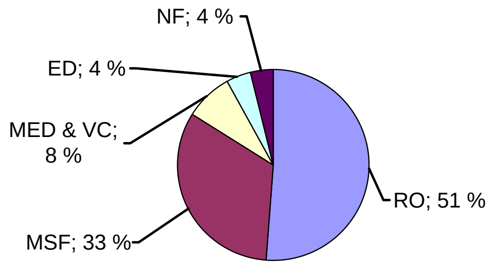

Fig. 5. Global installed desalting capacity by process (IDA Desalination Yearbook, 2007) [2,3].

1.4. *Why SWRO plants*

Water desalination by the technique of reverse osmosis has proved to be the lowest energy consuming technique according to many studies. It consumes nearly around half of the energy needed for thermal processes [1–4]. Also, the modularity of reverse osmosis units, their simplicity of operation, their compact sizes and lower environmental impacts give them priority to be used for water desalination in remote areas. Water desalination by reverse osmosis units removes not only inorganic ions but also organic matters, viruses and bacteria. Reverse osmosis is widely used around the world; indeed, reverse osmosis processes accounted for 59% of contracted desalination capacity as of September 2008, having grown at a rate of 17% per year since 1990 [2].

The globally installed desalting capacity by process in 2007 is shown in Fig. 5.

Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity [2].

1.5. *Why energy recovery devices (ERDs) are used in SWRO plants*

Energy recovery devices (ERDs) are employed in nearly all seawater reverse osmosis plants. The high operating pressures and low recovery rates produce concentrate reject streams containing significant quantities of energy. Energy costs are one of the more significant costs in the life cycle cost of a plant, accounting for up to 45% of lifecycle costs [1–4]. Therefore, it is economically infeasible to operate SWRO plants without energy recovery devices. Conversely, brackish water reverse osmosis (BWRO) systems have low operating pressures and high recovery rates. As a result, the concentrate streams from these systems contain significantly less energy available for recovery. Due to these factors, many BWRO plants do not employ energy recovery technologies.

1.6. *Objectives*

This paper presents a comprehensive description and overview of the various methods used for energy recovery in RO systems. Special attention is given to the use of energy recovery devices in seawater RO desalination. Among the various ERDs systems, the ones that have been used, or can be used, for SWRO desalination are reviewed at different design configurations. These include turbines, turbochargers, and isobaric devices. Finally, performance is compared for SWRO systems equipped with the different types of energy recovery devices (specific power consumption kW h/m^3, Energy saving%, and the corresponding cost saving).

2. RO systems

2.1. *RO energy recovery process*

Electricity consumption is a main cost component of the overall water production cost of SWRO. The RO reject stream (concentrate) contains most of the energy supplied to the seawater feed to the desalination process by the high pressure pumps. Consequently recovery of this energy and its utilization to reduce the overall energy demand of SWRO is one of the major optimization issues during the design of a RO seawater desalination plant. Today, there are various energy recovery technologies available on the market. All technologies apply the same basic principle of exchanging energy between the reject stream and the feed seawater stream. Available systems for energy recovery can be summarized as follows:

- Energy recovery turbines (ERT), mostly with Pelton wheels.
- Pressure exchanger (PX), which is an isobaric device that uses a rotating ceramic rotor as the main element and allows the feed and concentrate to have direct contact.
- Dual work exchanger energy recovery (DWEER), which is an isobaric device that uses pistons and valves to separate seawater feed and the concentrate return.
- Turbocharger, which is a turbine driven centrifugal pump, mostly applied.

2.2. *Different devices used for brine-stream energy recovery*

As stated above, the energy efficiency of seawater RO is heavily dependent on recovering the energy from the pressurized concentrate (brine). This was recognized and investigated several years before it became commercially viable. With brackish water, much higher water recovery ratios are possible, meaning that there is much less energy in the concentrate, which makes brine-stream energy recovery less critical. Different RO-ERDs configurations are given in details in Appendices A and B (Fig. 6).

The following discussion applies mostly to seawater RO [5–33,35].

2.2.1. *Pelton wheel*

In large systems, Pelton-wheel turbines are commonly employed. They are simple, reliable and very well proven in the field, but they are far from perfect. Their efficiency is usually significantly below what might be expected in a hydropower plant,

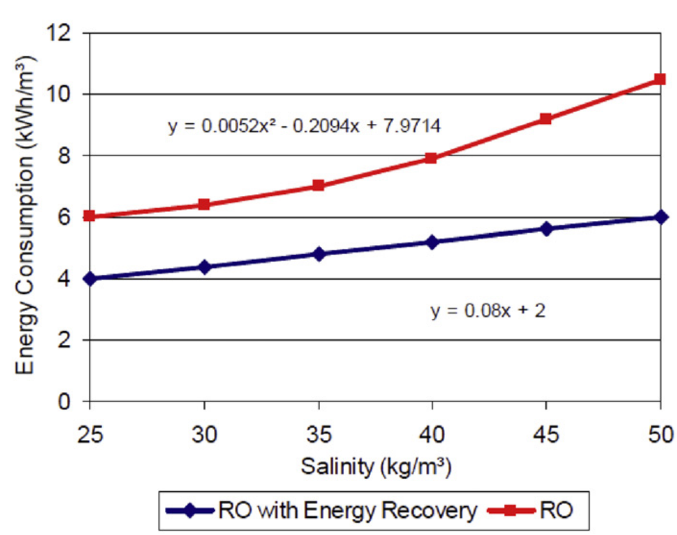

Fig. 6. Specific electricity consumption of reverse osmosis plants with and without energy recovery system as a function of raw water salinity [5].

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first, because they are coupled to the shaft of the main high-pressure pump, which is really too fast, and second, because the buckets tend to be rough, due to cost-cutting in manufacture and corrosion in service [5]. Furthermore, seasonal variations of flow and pressure in a RO plant can be significant, due to variations in water demand, feed water temperature and the condition of the membranes. The efficiency of a Pelton wheel can be significantly reduced when operating away from the design flow and pressure. Lastly, the energy that is recovered then has to go back through the main pump, suffering a further loss before it can usefully be applied to the RO membranes (Fig. 7).

In the light of the modest efficiency offered by Pelton wheels in RO systems, several manufacturers have developed alternative brine-stream energy recovery mechanisms. Healthy competition in this market has led to a steady improvement in the energy efficiency of seawater RO. In no particular order, the leading technologies are the Hydraulic Turbo Booster, the Dual Work Exchanger Energy Recovery (DWEER) and Energy Recovery Inc. (ERI's) Pressure Exchanger.

2.2.2. Hydraulic turbo booster

The Hydraulic Turbo Booster is manufactured by Fluid Equipment Development Co. (www.fluidequipmentdev.com). It comprises a single-stage radial inflow turbine and a single-stage centrifugal pump on the same shaft, but totally independent of the motor-driven pump. This independence allows the rotational speed of the Turbo Booster to be chosen to optimize its efficiency rather than being fixed by the electric motor. It also facilitates throttling arrangements: control valves that are used to fine-tune membrane pressure. Furthermore, the Hydraulic Turbo Booster can discharge the concentrate at above ambient pressure (Fig. 8).

2.2.3. The dual work-exchanger energy-recovery

The dual work exchanger energy recovery (DWEER) is manufactured by DesalCo Ltd. (www.dweer.com). It comprises two cylinders, each with a free piston. During one stroke, high-pressure concentrate water pushes the piston in one of the cylinders, which pressurizes the feed water on the other side of the piston. At the same time, low-pressure feed water pushes the piston in the other cylinder, which pushes the old concentrate out of the system. On the other stroke, the pistons reverse roles. Automatic valves are used to control and coordinate the flows into the two cylinders, and their design is central to the DWEER technology.

Notice, in Fig. 9, that an additional (motor-driven) pump is required to make up for the small pressure loss that occurs to the concentrate in the membranes and the work exchanger. An excellent review of large-scale work-exchanger energy recovery mechanisms, leading up to and including the DWEER, is presented by Rahman [5].

2.2.4. ERI's Pressure exchanger

The pressure exchanger is manufactured by Energy Recovery Inc. (www.energy-recovery.com). It is a form of work exchanger, but has 12 *cylinders* with no pistons. The cylinders are co-axial around the circumference of a ceramic rotor, rather like the holes in the magazine of a revolver.

As with other work exchangers, high-pressure concentrate water pushes pressurized feed water through one cylinder, while low-pressure feed water pushes the old concentrate out of another. The absence of a piston allows the water to mix a little, which increases the concentration of the feed slightly but is acceptable in moderation. The automatic valve gear required in other work exchangers is replaced by the rotation of the cylinders past stationary inlet and outlet ports. The rotation is powered by the flow of water through the device, and the speed of rotation is critical to minimizing the mixing (Fig. 10).

2.2.5. Relative efficiencies

The relative efficiencies of the four energy recovery mechanisms just described are the subject of much debate. It is meaningless to compare the efficiencies of the mechanisms themselves since their outputs have different forms: The Pelton-wheel gives mechanical

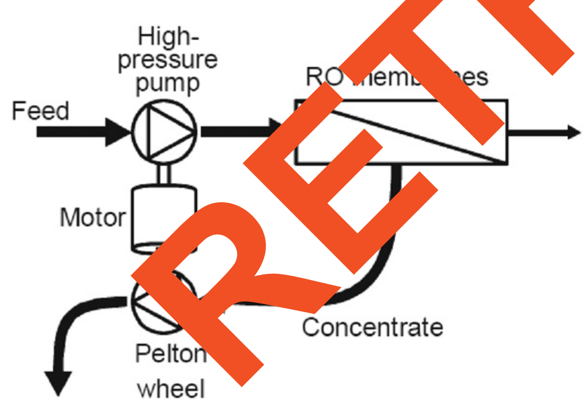

Fig. 7. Pelton-wheel energy recovery [5].

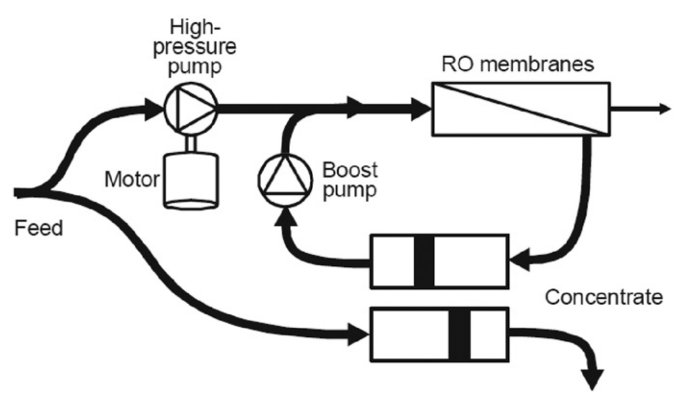

Fig. 9. DWEER work exchanger energy recovery [5].

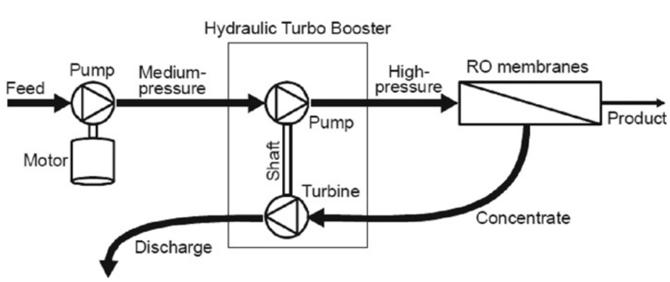

Fig. 8. Hydraulic Turbo Booster energy recovery [5].

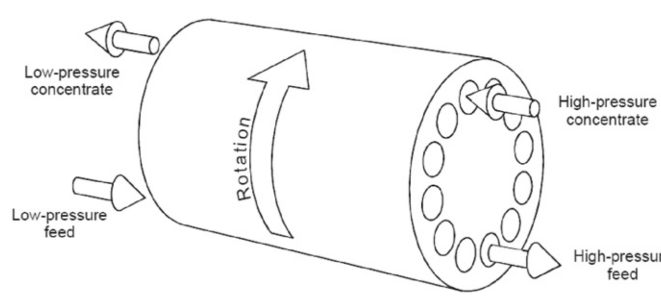

Fig. 10. ERI's pressure exchanger [4].

torque. The Hydraulic Turbo Booster raises the pressure of an arbitrary flow of water. The DWEER raises the pressure of a flow of water equal to that of the concentrate, and requires a further pump. ERI's pressure exchanger is similar, but involves some mixing of the flows.

In order to compare the efficiencies at all, the mechanisms must be considered within an RO system. The difficulty then is that parameters and efficiencies of all the other system components come into play and, depending on these, any of the energy recovery mechanisms can appear in a favorable light [5]. Losses in control mechanisms such as throttling valves and variable speed drives also need to be accounted for, as do seasonal variations in operating points.

As a guide, to choose and compare between the different types of energy recovery devices, the efficiency figures are given in Table 1. Also, the detailed conclusive comparison is tabulated in Appendix C.

2.2.6. Vari-RO

The Vari-RO combines water hydraulics with oil hydraulics. Three pistons are used to achieve the high-pressure pumping of the feed. These are driven by both the high pressure concentrate and the oil hydraulics, which is powered by a motor. Computer controlled valves direct the high-pressure concentrate between three different cylinders. Importantly, they open and close at zero flow in order to minimize transients. A prototype was demonstrated and further developed for solar application [5,6].

2.2.7. Energy recovery in small-scale RO

Small reverse-osmosis systems are often built without any energy recovery mechanism. They have a manually operated needle valve or pressure-operated relief valve to control the back-pressure in the concentrate. This keeps the capital cost down but is very wasteful of energy. Typically, 70% of the input power is wasted in the valve and, consequently, such systems often consume more than 10 kW h/m^3, making them very expensive to run.

Turbines tend to have poor efficiency at small size. Some investigators looked into the possibility of using a Pelton wheel for energy recovery in a 3-m^3/d seawater RO system. It needed a jet size of less than 1 mm acting on a wheel of diameter ~300 mm. High windage losses were expected, together with high manufacturing costs, and, in general, the approach was considered impractical.

For energy recovery in small-scale RO systems, positive-displacement devices generally offer much higher efficiencies. The DWEER work exchanger and ERI's pressure exchanger are positive-displacement devices but are not currently manufactured at small sizes. ERI did produce some small-scale pressure exchangers but found that they were prone to fouling; presumably this is less of problem in larger pressure exchangers with larger clearances. Other than ERI's pressure exchanger, most positive-displacement energy recovery mechanisms involve high-pressure valves that need to operate with precise timing to ensure a smooth flow of water. Combining this precision with corrosion-tolerance of concentrated seawater is very challenging, and many design concepts have failed in practice [5,36].

Table 1
Typical efficiency of energy recovery devices [5,6].

Energy recovery system	Efficiency (%)
Francis Turbine	76
Pelton turbine	87
Turbo charger	85
Work exchanger	96
Pressure exchanger	96

2.2.7.1. Energy recovery pumps. Integrated designs, combining brine-stream energy recovery with positive-displacement pumping, were developed by Bowie Keefer during the 1980s. He patented a hand operated pump with energy recovery for application to seawater RO. The patent also suggested that the device could be operated by the reciprocating action of a traditional water-pumping wind turbine. Later, he patented a shaft driven energy-recovery pump [5]. This was based on a standard plunger pump, but with positive-displacement energy-recovery added between the crank assembly and the plungers. The plungers also served as spool valves for the energy-recovery. Prototypes were built and demonstrated very good energy efficiency, including some that were operated from PV. This work showed great promise, but unfortunately was not continued; perhaps the cost of manufacture was too high.

2.2.7.2. Hydraulic motor. Oil-driven hydraulic motors are very widely used in many industrial applications; they are very efficient and very well proven. Water-driven hydraulic motors are relatively new but are used for example in the food industry, where risk of hydraulic oil leakage is not acceptable. Danfoss manufacture a range of small water-driven hydraulic motors for such applications. The Danfoss motors have axial pistons acting on a swash-plate to rotate the shaft. They are lubricated by the driving water. Dulas Limited demonstrated the use of a Danfoss hydraulic motor for energy recovery in a small seawater RO system. This reduced the specific energy consumption from 13 kW h/m^3 for a system using a needle valve, to around 5.6 kW h/m^3 — a significant improvement in the context of PV-RO. The work described in this thesis was founded on the success at Dulas and, in the early stages, employed a similar Danfoss hydraulic motor. However, testing at CREST indicated slightly lower efficiencies and corrosion problems, and the hydraulic motor was dropped from the design, in favor of the Clark pump. It was reported that, some researchers, who are developing PV-RO, were using Clark pumps but have now switched to a hydraulic motors [5,6].

2.2.7.3. Clark pump. The Clark pump is a little like the dual work exchanger (Fig. 11), except that the two cylinders are in-line and the two pistons are connected by a rod. The rod creates a difference in the effective areas on the two sides of each piston, which allows the relative flows to be adjusted by design. Furthermore, having the two pistons connected allows energy from the feed to be added to that of the concentrate, yielding an output pressure higher than that of the concentrate. Hence, the Clark pump is sometimes described as a *pressure intensifier*. A further description of its operation is presented below, but it is perhaps best understood from the animation at: http://www.spectrawatermakers.com/technology/overview.html.

The basic mechanics of a Clark pump are shown in Fig. 11a. The two pistons are solidly connected by the rod, and this assembly reciprocates inside the cylindrical housing. In Fig. 11b the medium pressure and the concentrate pressure both act to push the piston assembly to the right, thus driving the high pressure, as shown. At the end of stroke, an internal mechanism reverses the ports, as shown in Fig. 11c, and the piston assembly travels back to the left, until it again reverses.

The general arrangement of the two pistons and the rod, and its application to RO systems, was presented in patents many year ago [5,6]. But, it was not until a practical valve-operating mechanism was developed and patented by Clark Permar (hence the name *Clar* pump) that the arrangement became commercially

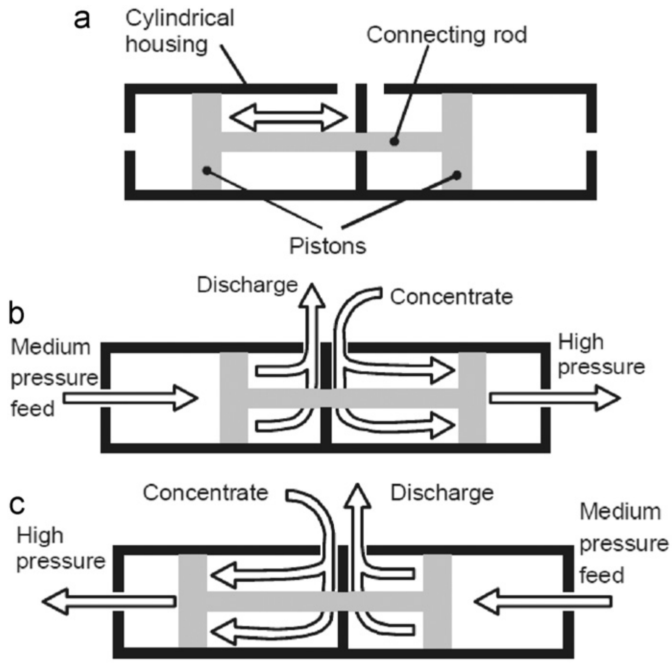

Fig. 11. Basic mechanics of a Clark pump [5].

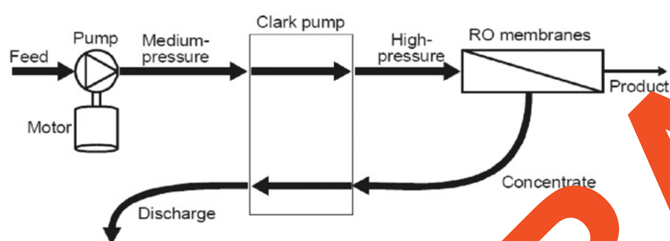

Fig. 12. Simple configuration of a Clark pump in an RO system [5].

viable. Rahman et al. [5] reported that [illegible] licensed the design to Spectra Watermakers Inc. who developed a commercial product during 1997. It was aimed at the yachting market and was sized to suit a single 2.5 by 40-in spiral-wound seawater RO element.

The simplest configuration of a Clark pump in an RO system is shown in Fig. 12. It requires only one motorized pump and no pressure regulation mechanism. The water recovery ratio (product flow to feed flow) is the ratio of the cross-sectional area of the rod to that of the piston. This simple configuration is marketed by spectra and achieves a specific energy consumption as low as 3.2 kW h/m^3 for seawater at 35,000 ppm, 25 °C [5], which is excellent for a small system. CREST obtained a Clark pump in August 2000 and tested its performance thoroughly. Its energy efficiency is excellent and, importantly, this is maintained over a very wide range of flow and pressure. Two configurations of single and two motors which are shown in Fig. 13.

Recognizing the need to increase product flow per Clark pump, spectra proposed the configuration shown in Figs. 6–14. The introduction of the second pump increases both the feed flow to the membrane array and the recovery ratio. The new recovery ratio can be adjusted by the ratio of the pump displacements, assuming they are positive displacement pumps. The feed from the second pump in Fig. 14 does not go to the first membrane element, but rather is delayed and injected before the fourth. The thinking here is that this reduces the buildup of concentration through successive membrane elements.

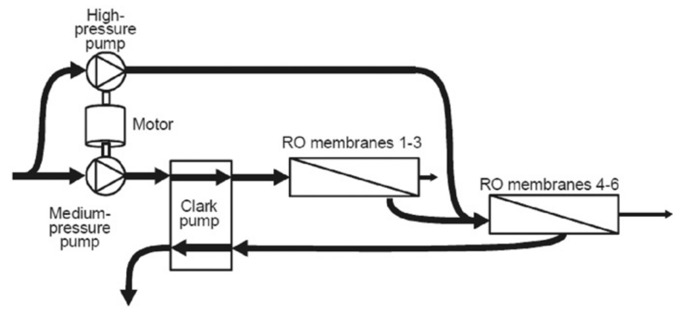

Fig. 13. Delayed injection—single motor [4].

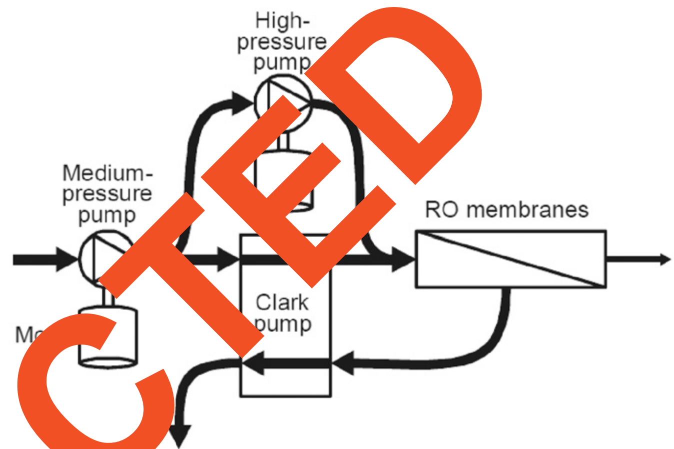

Fig. 14. Two motor—variable recovery ratio.

A system using two variable-speed motors is shown in Fig. 14, and this is the general arrangement finally adopted for the PV-RO system. The independent control of the two pump speeds provides control over the water recovery ratio, and this is especially valuable in a batteryless PV-RO system because it enables the water production to be maximized as the available sunlight varies through the day. The next step was to determine how the recovery ratio should be varied in order to achieve this maximum.

3. Performance comparison of the SWRO with different types of ERDs

Farooque et al. [7] have explicitly described the performance and efficiency of various ERDs used in several seawater reverse osmosis (SWRO) desalination plants in Saudi Arabia. They compared the efficiencies of these ERD systems based on operating conditions for 1 year. Also they assessed their effect on the high-pressure pump's total energy consumption and savings, along with an assessment of the energy loss incurred during the process stream of desalination plants. The mean efficiency of the assessed ERDs varied from 3.2% to 65%, enabling 1.5to 27% savings on the high-pressure pump's total energy consumption. The mean power consumption of the pump ranged from 5.56 to 7.93 kW h/m^3. A significant amount of energy was wasted due to throttling, which consumed about 6.4%–21.8% of the total energy supplied to the high-pressure pump.

A brief description of the energy recovery technology used during the desalination process in large plants was provided by Peñate and García-Rodríguez [8]. They described the modifications needed for the replacement of Pelton turbines with isobaric chamber devices. An exhaustive examination of the achievable levels of energy efficiency of these systems was also done.

Table 2
Comparison between the different three types of ERDs [5,6].

Description	Isobaric PX devices	Centrifugal Turbocharger	Centrifugal Pelton wheel
Efficiency (%)	98	81	78
Efficiency curve	Flat	Curved	Curved
Mixing (%)	2–3	0	0
HP pump size	Sized for partial membrane feed flow, full membrane feed pressure	Sized for partial membrane feed pressure, full membrane feed flow	Sized for partial membrane feed pressure, full membrane feed flow
Footprint requirement	Relatively small compared to overall SWRO equipment	Relatively small compared to overall SWRO equipment	Relatively small compared to overall SWRO equipment
Periodic maintenance	No	No	Yes
Modularity	Yes	No	No

An emerging technology based on the principle of pressure work exchange was put forth by Al-Hawaj [9]. The device employed a rotating member with multiple free-sliding double-sided ball pistons that functioned on pressure exchange between fluids that were pressurized at varying levels. He also discussed the technical aspects of the work exchanger apart from assessing the predicted efficiency based on qualitative comparisons with other ERDs.

William [10] provided a historical overview of large scale ERDs that work on the principle of work exchange, beginning with the application of SWRO in 1975 to the present state of technology in desalination. As is evident from their work, technology based on work exchange has evolved tremendously since the time of its inception. They also described twelve years of the application of this technology in desalination plants.

Furthermore, an important and original calculation model was developed by Migliorini and Luzzo [11] to account for the different conditions of seawater based on carbonate equilibrium. The use of this classical equilibrium system for calculations enabled the formulation of a complete mass and chemical balance of the system, along with the other characteristics of water. This model of calculation is not dependent on the characteristics of the membrane and so, can be used for a quick designing of the plant.

Farooque, Ali and Al-Reweli [12] have stated that Francis Turbines were popular in the early days of SWRO technology owing to their ease of use and simplicity. As briefly discussed in the previous section, Francis Turbine (FT) uses kinetic energy derived from brine coupled with the pump motor of the main feed to minimize the loss of energy during transfer from one fluid to the other. Due to their limited efficiency, which was below 75%, they lost their popularity and have been replaced by more efficient devices.

Baig [13] has investigated the theory of energy double dipping in hydraulic to mechanical assisted pumping devices, Pelton wheels and Francis Turbines. He stated that the maximum efficiency of Pelton wheels ranges between 80 and 85%. He emphasized the fact that the Pelton wheel and the FT share a common feature of transferring the energy recovered from brine back to the high pressure pump by coupling them to a common shaft. Computing total loss of energy, the energy lost by the high pressure pump and the reduction in the wheel's energy efficiency were taken into account. This is what was referred to as "double-dipping" in energy efficiency.

William T. Andrews [14] described the DWEER energy recovery device to have two pressure vessels arranged in parallel. To avoid interrupting the flow of the reject, while one vessel is under operation, the other vessel is stationary, and has fresh feed. The pressure from the reject stream is transferred to the feed stream through a piston and the intermixing between the feed and reject is kept at a bare minimum. As the piston is designed in such a way that it has the least drag, the energy transfer between the two fluids is theoretically 100%. Therefore, the direct exchange of energy between the two fluids, i.e. the reject and the feed is highly efficient when compared to ERDs that rely on the conversion of energy by shaft of the turbine based on the centrifugal principle. In the DWEER system, by the time the piston in the operating vessel completes its working stroke, the other vessel is completely filled with feed and the functions are switched.

MacHarg [15] demonstrated how the PX device pressurizes the feed water directly. This is in contrast with the energy recovery turbine, where the energy of the concentrate is converted to mechanical energy by rotating the shaft and thus recovering energy. Because of the direct pressurization with PX device, there are no losses due to absence of the transformation process in this case. This results in extremely high energy efficiency achieved by the PX devices. This will considerably reduce the power consumption of the SWRO plant employing these PX devices. The other researches [16–34] are also emphasizing on the necessity of ERDs for energy saving in SWRO plants.

Today, however, over 80% of new SWRO plants are being designed and built to utilize the last type of ERDs which is known as isobaric-chamber ERDs. Isobaric ERDs such as pressure exchanger (PX) device are positive displacement devices that operate with energy transfer efficiencies as high as 98% [6]. High SWRO plant operating efficiency can be obtained over a wide range of membrane water recovery rates, typically between 35% and 50%. Recovery rates can be adjusted in response to changes in seawater temperature or salinity or as the membrane elements age.

Removing the conventional ERDs and installing modern isobaric ERDs makes it possible to reduce the power consumption of existing systems by as much as 60%. Such retrofits can also significantly increase the capacity of existing systems while adding little or no additional power requirements. These benefits can be realized at a fraction of the cost of constructing new plants. For these reasons, many owners of legacy desalination plants worldwide are upgrading their processes by incorporating isobaric ERD technology (Table 2).

4. Energy consumption of SWRO with different types of ERDs

The saving results for the studied three cases compared to the reference case are shown in Table 3 [27].

Also, the saving from using the studied ERDs was investigated by Energy recovery Inc. [21–28]. The benefits of ERDs for overall SWRO process energy reduction is illustrated in Fig. 15. From this figure, starting with the Jeddah-1 plant (Saudi Arabia) which had no energy recovery, it consumed over 8 kW h/m^3 in the SWRO portion of the process. SWRO energy consumption was first lowered by implementing Francis Turbines as was done in Las Palmas, Gran Canaria. Then by Pelton turbines as was done in Trinidad. It should be noted that the Pelton turbines in the

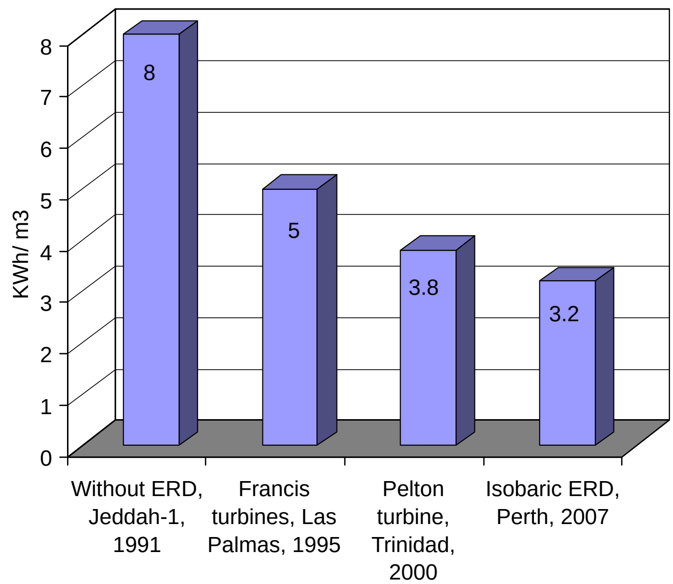

Fig. 15. Evolution of SWRO energy consumption by field applications [27].

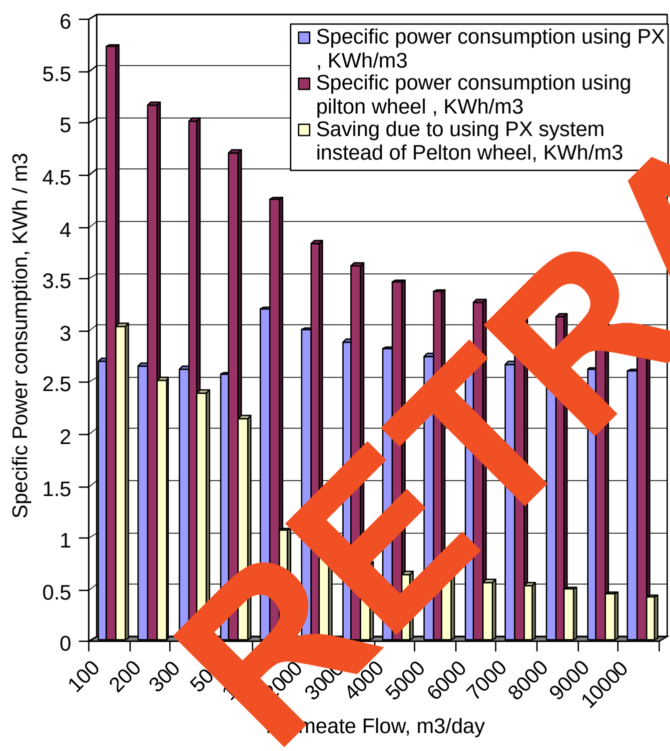

Fig. 16. Specific power consumption at different SWRO capacities (product flow) for different ERDs [27].

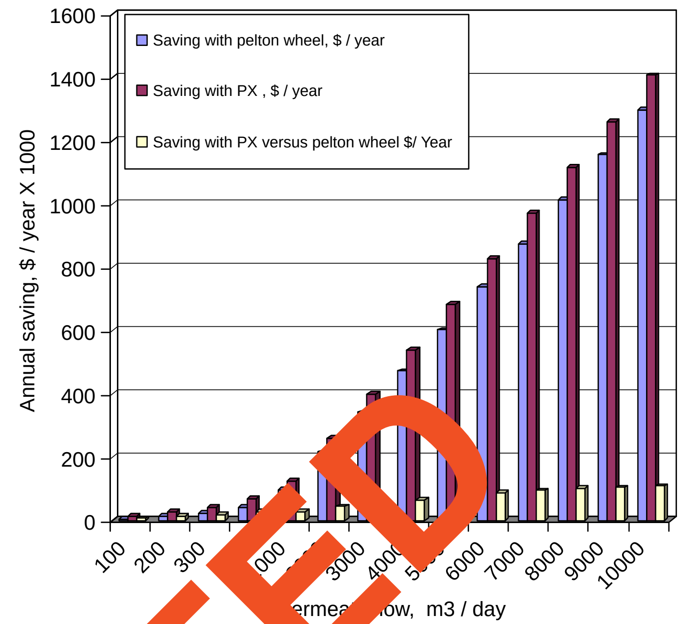

Fig. 17. Annual cost saving comparison between at different plant capacities [26].

Table 3
SWRO specific energy consumption and percentage of saving for the studied three cases compared to the reference case in (kW h/m^3), % respectively [27].

Energy saving (kW h/m^3)	ERD type	Medium system	Large system
Reference case	Without ERD	10	8
Case 1	Pelton turbine	4.32 (56%)	2.72 (66%)
Case 2	Turbocharger	4.26 (57.4%)	2.69 (66.4%)
Case 3	Isobaric ERD	3.09 (69.1%)	2.22 (72.3%)

Table 4
Summary results of energy saving at medium size and large SWRO plants for the studied cases [26].

Energy saving (kW h/m^3)	ERD type	Medium system	Large system
Reference case	Without ERD	10	8
Case 1	Pelton turbine	4.25 (57.5%)	3.01 (62.4%)
Case 2	Turbocharger	N/A	N/A
Case 3	Isobaric ERD	3.19 (68.1%)	2.59 (67.6%)

Table 5
Summary results of cost saving at medium size and large SWRO plants for the studied cases [27].

Cost saving (\$/year)	ERD type	Medium system	Large system
Case 1	Pelton turbine	97×10^3	125×10^3
Case 2	Turbocharger	N/A	N/A
Case 3	Isobaric ERD	1297×10^3	1406×10^3

Trinidad plant are very large and considered as state-of-the-art. Nevertheless, the isobaric ERDs and other process improvements cut SWRO plant energy consumption from approximately 3.8 kW h per cubic meter of permeate produced (kW h/m^3) to 3.2 or about 16% [27].

Furthermore, Figs. 16 and 17 show that isobaric ERDs can reduce the energy consumption and cost as well more and more at higher capacities of SWRO plants.

Hence, the SPC and cost saving figures are included in Tables 3 and 4 for the medium size and large of SWRO plants (1000 and 10,000 m^3/day respectively) (Table 5).

From Figs. 16 and 17, it is clear that, the energy and cost saving are:

1. *For case* 1: the percentage of energy saving is 57.5%:62.4%. The corresponding cost saving is 97×10^3:125×10^3 \$/year depending on the plant capacity.
2. *For case* 3: the percentage of energy saving is 67.6%:68.1%. The corresponding cost saving is 1297×10^3:1406×10^3 \$/year depending on the plant capacity.
3. *For case* 2: it is not included in the calculation program.

Note that, using a simple calculation program (excel sheet), made by Energy recovery Inc. [22,26], the results shown in Figs. 7 and 8 and Tables 3 and 4 are obtained under the following operating conditions, see Appendix D for details [22,26]:

1. RO feed pressure = 69 bar
2. Membrane differential pressure = 2.5 bar
3. Feed-water salinity = 49,160 PPM
4. Brine pressure at exit from ERD = 2 bar
5. Energy cost = 0.08 $/kW h
6. Number of working days/year = 325.

5. SWRO energy consumption analysis

Energy is consumed throughout the SWRO process for conveying and pressurizing water. A breakdown of energy use in a large state-of-the-art plant is shown in Fig. 18. These data indicate that 68% of the power consumed in a SWRO process goes to the high pressure pumps that feed the RO membranes, even in modern plants using low-energy membranes and high-efficiency pumps.

6. Other environmental factors

Concern has also been raised about the potential environmental impact of concentrate discharges from desalination facilities. However, the majority of the known impacts are from therm[al] (distillation) facilities from which copper and other metals leached from the process are discharged. Membrane desalination facilities, which use significantly less metal and operate at m[uch lo]wer temperatures, do not cause such impacts. Nevert[hel]ess, [so]me desalination plants assure zero environmental imp[act] by di[schar]ging the seawater concentrate far out to sea i[illegible]nts. At the Perth desalination plant, for example, th[e c]oncentra[te p]ipeline extends 470 m from shore. The velocity o[f the] discharge i[s u]p to 4 m/s through nozzles spaced at 5-meter interv[als] to ensure total mixing of seawater concentrate wit[hin] 50 m of e[ach] side of the pipeline.

Less concern has been raise[d ab]out t[he] environmental impacts of seawater intakes. Intake syste[ms are] design[ed] to minimize the entrainment of solids a[nd ma]rine l[ife] that [m]ust be removed by the pretreatment sys[tem] be[for]e the [wate]r flows to the SWRO process. Open intak[es] are id[ea]lly placed in flowing currents to assure uniform, clean [sea]water[illegible] intake velocities are minimized to prevent entr[ain]ment. Beach wells and ocean-floor subsurface intakes are also [wi]dely employed.

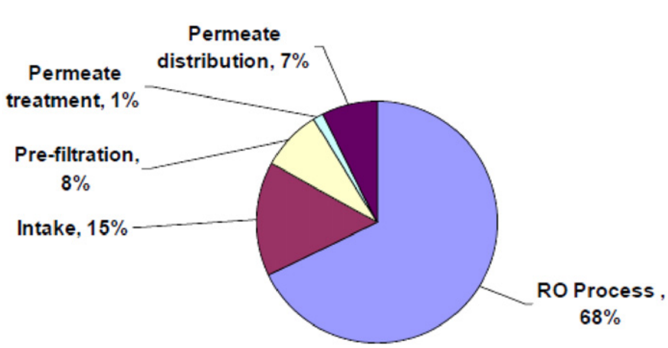

Fig. 18. Estimated power consumption in a 50 million gal/day SWRO plant [2–4].

7. Conclusions

The global demand for fresh water continues to grow while supplies dwindle. Desalination of seawater with reverse osmosis membranes and energy recovery devices has become an affordable means of water supply.

The use of ERDS in SWRO desalination appears nowadays as a reasonable and technically attractive option towards the emerging and stressing energy and water problems.

The present review is done to study the effect of the using three different types of ERDs on the performance of SWRO plants. The studied cases are Pelton wheel (case 1), turbocharger (case 2), and Isobaric pressure exchanger PX devices (case 3).

Using ERDs systems, the energy saving is 56%:66, 57%:66.4%, and 67%:72% for case 1, case 2, and ca[se 3 r]espectively. This leads to annual cost saving of 97 × 10^3:1[illegible] × 10[illegible]ear for cases 1 and 2, 1297 × 10^3:1406 × 10^3 $/year [for c]ase 3, de[pen]ding on the plant capacity. As a result, most SWR[O pla]nts bei[ng] built today are expected to use ERDs devi[ce]s.

In the light of th[e] above [m]entio[ned] significant savings achieved by using ER[Ds in] RO [pl]ants, it is recommended that:

- Retrofitting i[s r]ecommen[ded f]or existing RO plants to use the best ERD [to] achieve t[he] higher saving of energy.
- ERDs devices ha[ve] to be considered when buying new RO pla[nts].

Appe[ndix] A. R[O] design configurations [33]

[M]odule arrangement is an important part of designing a RO sy[stem. A]rrangement of module is determined by feed water [c]omposition and product water quality needed. There are vari[e]ties of arrangement used by brackish water researchers to [o]ptimize the performance of RO system. On average, brackish water RO system could achieve about 90% water recovery with initial pressurization reach up to 27 bar [33].

A.1 Single-stage

Simple single-stage module arrangement is shown in Fig. 4. The feed water is pumped into the RO module with a designated pressure by high pressure pump. It then splits into product water and reject water. Product water is filtered while the reject water is with higher saline than feed water. With efficiency independent of the water recovery and generated feed pressure, optimal water recovery is not influenced by efficiency of high pressure pump but specific energy consumption increases with decreasing pump efficiency.

Module arrangement shown in Fig. A1 is a single stage RO system with ERD. ERD could reduce energy consumption of RO system. It reduces optimal minimum energy location to lower

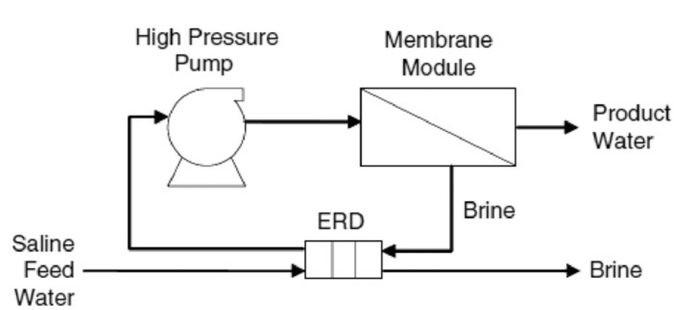

Fig. A1. Single-stage module arrangement ERD [33].

recoveries and SEC increases as efficiency of the pump reduces. ERD could reduce the energy consumption and operating cost of the system but initial cost of installation would be high.

A.2 Two-stage [33]

Two-stage system with booster pump is shown in Fig. A2. Booster pump increases the feed pressure from first module before entering the second module. System build with the booster pump depends on pressure of reject water from the first module. If the booster pump is not included, then the RO system must be operated above minimum brine or reject flow rate to prevent concentration polarization from occurring.

With a booster pump, the feed water pressure and water flux can be increased to an optimum value and second stage can be operated in nominal hydraulic conditions. Advantage of adding a booster pump is smaller membrane area which leads to higher total recovery rate and therefore reducing the electricity consumption and the investment costs.

This arrangement would able to increase recovery rate up to 83%. It able to reduce boron concentration in brackish water more economically and consumes lesser energy compare to ion exchanging by boron selective resins or use of special RO membranes developed for boron removal in low or natural pH. Boron concentration in the desalination product should be below 0.3 mg/l according to EU. This arrangement is also a very successful method for eliminating fluoride from brackish water. There are no operation changes in using SWRO membrane as part of BWRO system.

A.3 Two-pass

Two-pass RO system would able to provide product water with very low salinity. It is suitable for feed water with very high salinity. First pass would reduce water salinity and further reduction of salinity is done by second pass. Pressure of product water after first pass will be lower than the osmotic pressure of the second stage therefore pressure pump is needed to increase pressure from atmospheric to pressure between 20 and 40 bar which enables water pass the second membrane (Fig. A3).

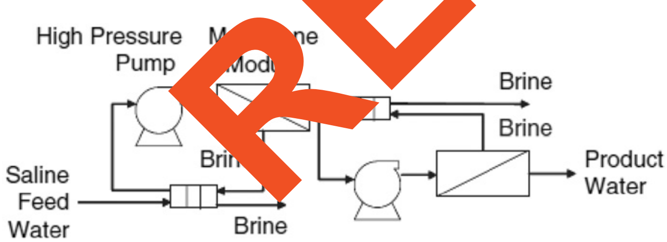

Fig. A2. Two-stages with ERD [33].

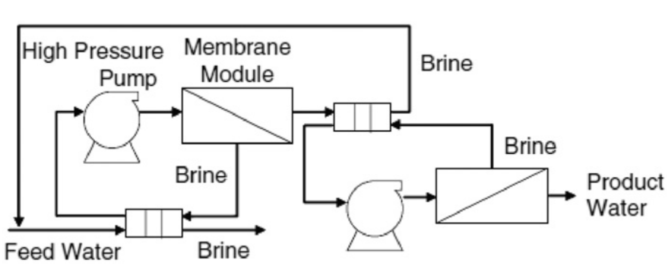

Fig. A3. Two-pass RO system without an ERD [33].

The second pass generally able to operate at high average permeates flux with recovery rate between 85% and 90% due to very low concentration of suspended particles and dissolved salts.

Two other variety of two-pass RO system is with inclusion of ERD as shown in Fig. 8 and with ERD and recycling the concentrate of the second pass to the feed of the first-pass (Fig. A4). The former have constant feed water salinity while recycling the

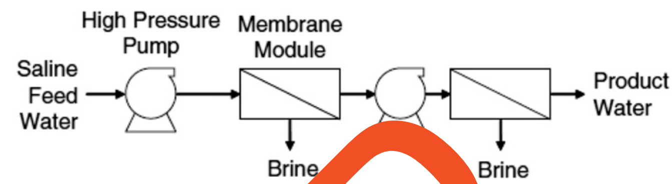

Fig. A4. Two-pass with ERD and recycling the concentrate of the second-pass to the feed water of the first-pass [33].

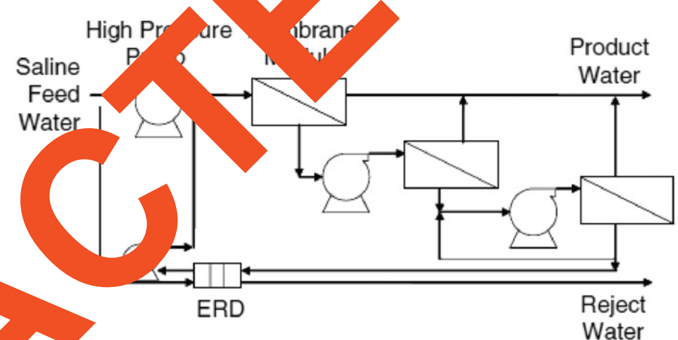

Fig. A5. Optimum module arrangement for feed concentration of 3000 mg/l [33].

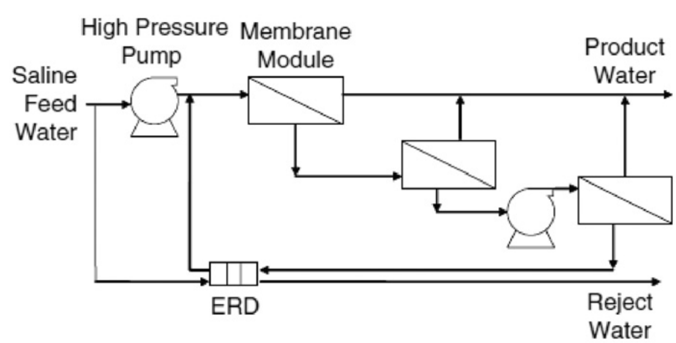

Fig. A6. Optimum module arrangement for feed concentration of 6000 mg/l [33].

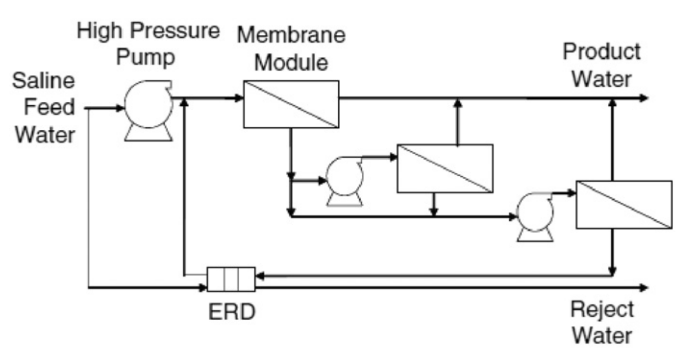

Fig. A7. Optimum module arrangement for feed concentration of 12,000 mg/l [33].

concentrate of the second pass to the feed stream of the first-pass reduces the salinity of feed water in the latter.

The choice between single stage configuration and two-pass configuration for same level of total water recovery and salt rejection depends on lowest energy consumption which can be compared when the applied pressure is equal or more than thermodynamic cross flow limit without energy recovery devices.

Generally most authors agree two-stage system is more energy efficient compared to single stage system, however, some authors pointed out that for brackish water, single stage system is the most cost-effective compared to two-pass system. Two-pass system would be energy efficient than single-stage if water recovery of single stage is below 50%.

A.4 Three-stage [33]

Lu et al. proposed three different optimum module arrangements based on simulation study which is three-stage system. The authors favored three-stage system oppose to single stage system. The proposed module arrangement is shown in Fig. A5 for feed water concentration of 3000 mg/l, Fig. A6 (6000 mg/l) and Fig. A7 (12,000 mg/l). In Fig. A5, brine from third module is partly recycled back for higher recovery while other flows to ERD. Fig. A6 shows much simpler module arrangement compared to the arrangement for feed water concentration of 3000 mg/l (Fig. A5). The arrangement is the same but with lesser number of pumps. In

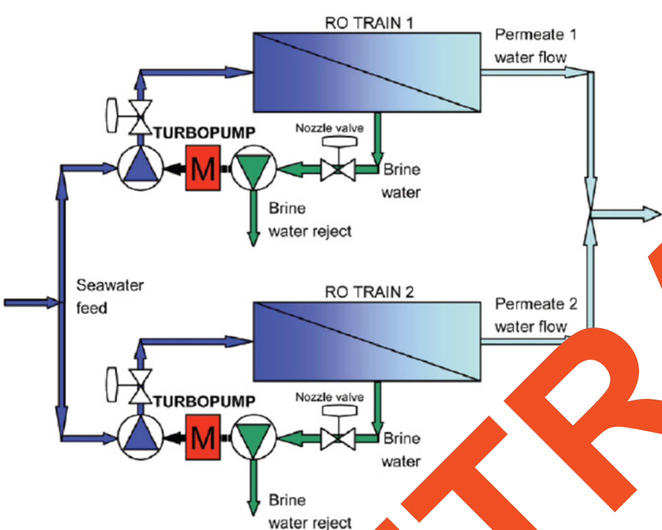

Fig. B1. 10,000 m^3/d SWRO plant diagram using Pelton turbine energy recovery devices [5].

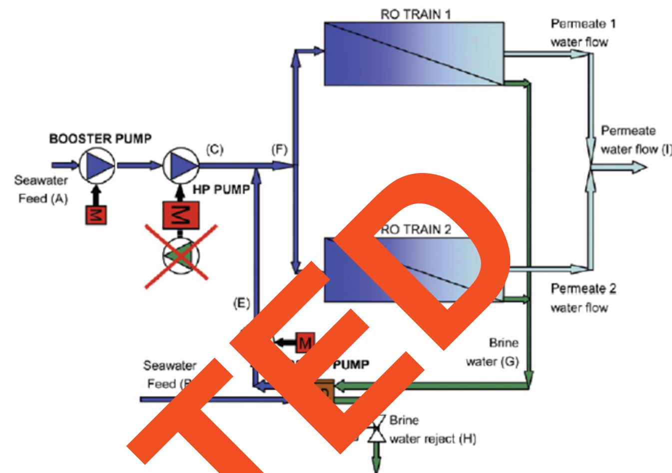

Fig. B3. Retrofitt proposed in an existing SWRO plant—isobaric energy recovery device in a two 5.000 m^3/d RO trains and a booster pump for the low-pressure feed water [5].

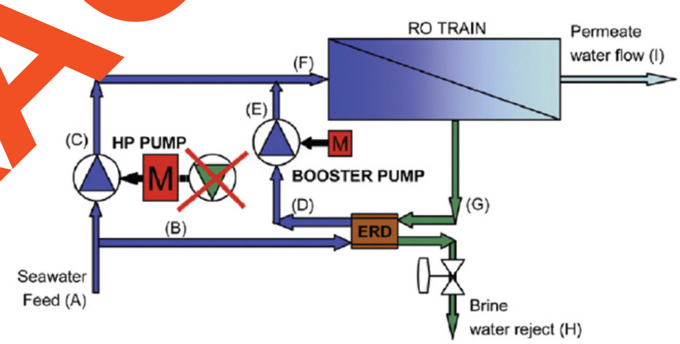

Fig. B4. Installation of an isobaric energy recovery device and higher RO train [5].

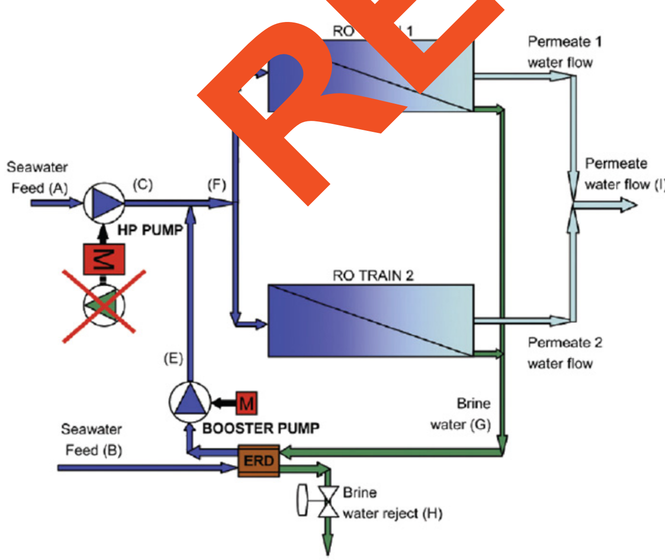

Fig. B2. Retrofitt proposed in an existing SWRO plant—isobaric energy recovery device in a two 5.000 m^3/d RO trains [5].

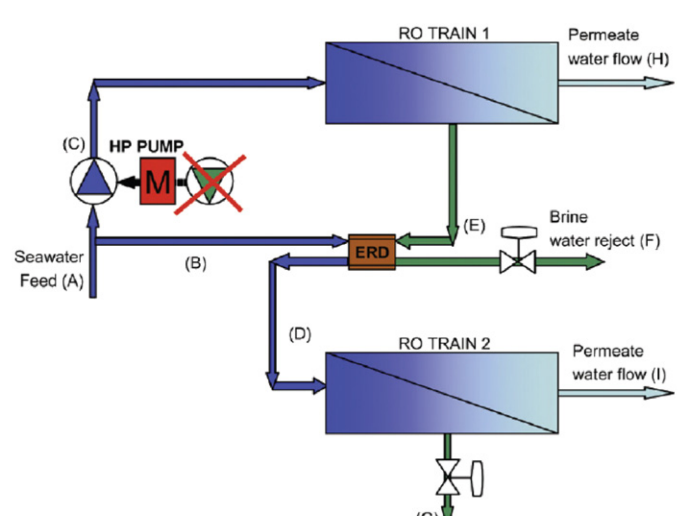

Fig. B5. Isobaric energy recovery device with a new RO train without BOP [5].

module arrangement as shown in Fig. A7, concentrate from first module splits into two, one flowing to second module after pressure is increased with a pump while the other flows to the third module through a pump.

Appendix B. SWRO-ERDs with different configurations [5]

See Figs. B1–B8.

Appendix C. Different ERDs conclusive comparison [5]

See Table C1.

Appendix D. Performance and cost equations [27]

With reference to Fig. D1, the energy required to operate the high-pressure portion of an SWRO system equipped with PX technology is the sum of the high-pressure pump and booster pump consumption. This energy is expressed in terms of the specific energy or the energy required per unit output of permeate

$$SE_{px}=(E_{HP}+E_{BP})/Q_P$$

$$SE_{px}=\frac{Q_{HP}(P_{HP}-P_F)}{\eta_{HP}\,\eta_{HPM}}+\frac{Q_{BP}(P_{HP}-P_{BPI})}{\eta_{BP}\,\eta_{BPM}\,Q_P} \quad (1)$$

where SE_{PX}, PX system specific energy; E_{HP}, high-pressure pump energy consumed; E_{BP}, booster pump energy consumed; Q_P, permeate flow rate; Q_{HP}, high-pressure pump flow rate; P_{HP}, high-pressure pump outlet pressure; P_F, high-pressure pump feedwater pressure; η_{HP}, high-pressure pump efficiency; η_{HPM}, high-pressure pump motor efficiency; Q_{BP}, booster pump flow rate; P_{BPI}, booster pump inlet pressure; η_{BP}, booster pump efficiency; η_{BPM}, booster pump motor efficiency.

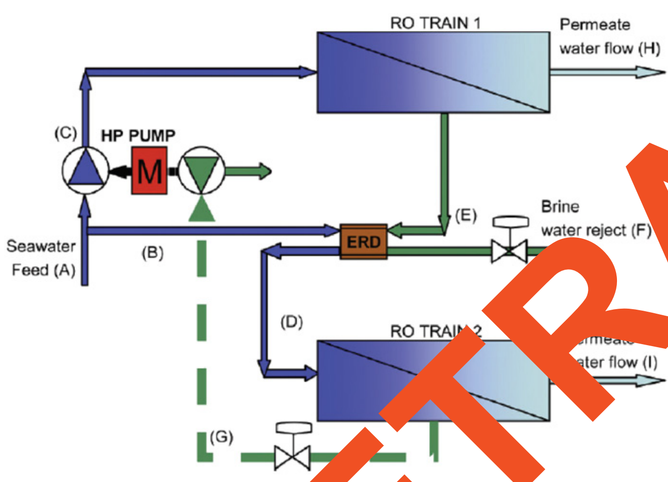

Fig. B6. Isobaric energy recovery device with new RO train without booster pump and Pelton turbine.

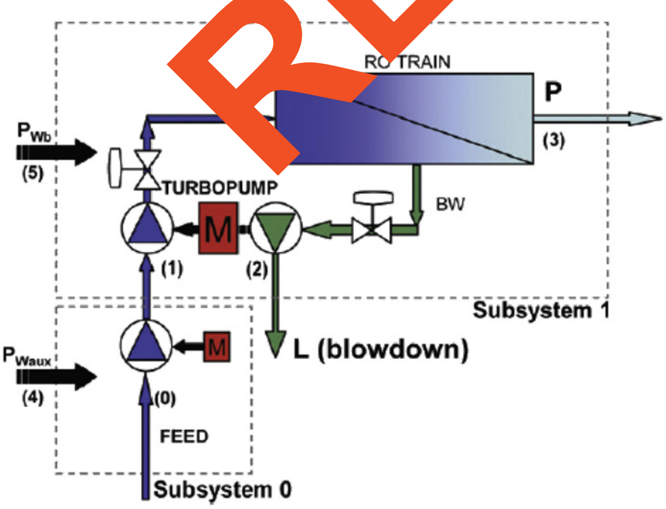

Fig. B7. Flow chart of the whole productive process for the analysis in the case of standard configuration (existing desalination plants with energy recovery device based on Pelton turbine).

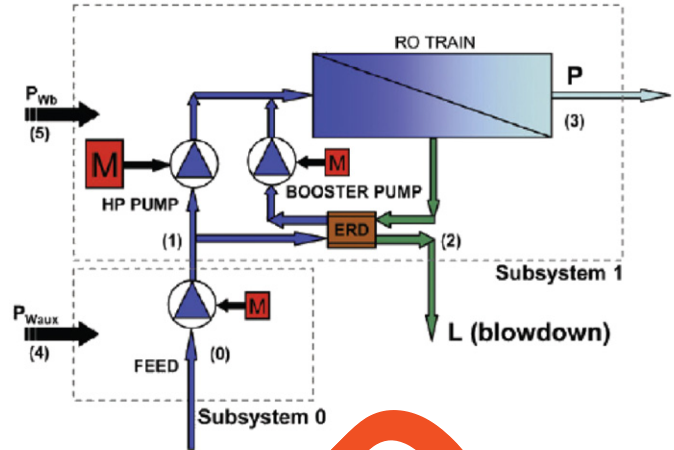

Fig. B8. Flow chart of the whole productive process for the analysis in the case of retrofitting desalination plants (installation of energy recovery device based on isobaric chambers).

The energy transfer efficiency of a PX device is derived with an energy balance. The hydraulic energy leaving the PX device is divided by the energy entering the device according to

$$\eta_{PX}=\frac{Q_{BP}P_{BPI}+Q_EP_E}{Q_BP_B+Q_{F'}P_{F'}} \quad (2)$$

where η_{PX}, PX efficiency; Q_E, system discharge flow rate; P_E, system discharge pressure; Q_B, membrane discharge flow rate; P_B, membrane discharge pressure; P_B, membrane discharge pressure; Q_F, PX feedwater flow rate; P_F, PX feedwater pressure.

Approximately 1–2.5% of the brine flow to the PX device is consumed as hydrodynamic-bearing lubrication, depending on system pressure, temperature and flows. The lubrication flow required by the PX device is supplied by the high pressure pump.

Since there is no physical barrier between the brine and seawater streams in the PX device rotor, these streams mix slightly. The ratio of the increase in membrane feedwater salinity divided by the system feedwater can be derived by mass balance or very closely approximated with the following equation:

$$SI=R(6.15\%) \quad (3)$$

where *SI*, salinity increase; *R*, membrane recovery.

Eq. (3) applies at "balanced flow" when the high- and low-pressure flows through the PX device are equal. No excess low-pressure flow or "over-flush" is necessary in a PX device.

PX efficiency: The pressure-transfer efficiency of a PX unit or PX array can be calculated with Eq. (1)

$$PX\ efficiency=\frac{\Sigma(pressure\ \times\ flow)_{out}}{\Sigma(pressure\ \times\ flow)_{IN}}\ \times\ 100\% \quad (4)$$

Mixing: In all commercially available isobaric ERDs, some contact between the brine and seawater streams occurs inside the device. As a result, these streams mix slightly. The resulting

Table C1
Different ERDs conclusive comparison.

Type	Class	Maximum efficiency (%)	Advantages	Disadvantages
Francis Turbine	Hydraulic to mechanical assisted pumping	75–80	1. Low capital cost 2. Direct flange connection to be preferred over clutch	1. Efficiency "Double Dip" 2. Narrow operating pressure and flow range 3. Lower efficiencies in regions with variable temperature ranges 4. Difficult to maintain and control due to clutch assembly 5. Not suitable for low flow ranges due to poor efficiency
Pelton wheel	Hydraulic to mechanical assisted pumping	80–85	1. Low capital cost 2. Easy in operation 3. Optimization of Pelton wheel and nozzle design for efficient kinetic to mechanical energy transformation 4. High efficiency maintained over the full operation range	1. Efficiency "Double Dip" 2. Distributor geometry induces dissymmetry and secondary flows at the [illegible] of the nozzle
ERT	Hydraulically driven pumping in series	90	1. Relatively low capital cost 2, Specifically designed for RO relatively small footprint and easy to install, operate and maintain 3. Used duplex grades of stainless steel corrosion resistant alloy parts 4. No electrical cooling or pneumatic requirements 5. Turbocharger and HPP are not directly connected providin[illegible] degree of flexibility	1. Limitation of [illegible] being able [illegible] recover 50–80% energy 2. Effici[illegible] decline in [illegible] with the efficiencies of im[illegible]er, nozzle and [illegible] 3. [illegible]ency [illegible]ine as the flow rate or pressure of the reject [illegible] strays from optimal
Recuperator	Hydraulically driven pumping in parallel	92–97	1. Directly transfer of brine hydraulic energy to feed hydraulic energy without going through shaft work 2. Seawater of the same flow and pressure as th[illegible] reject with no mixing 3. HPP required is about 60% smaller than tha[illegible] the traditional technology	1. High capital cost 2. [illegible]ompensate for the pressure drop across the mem[illegible]es (0.5–1.5 bar) and in the recuperator system (0.2–0.6 bar) a booster pump that can take high suction pressure is needed 3. Mixing, lubrication, overflush, high pressure differential, low pressure differential
DWEER	Hydraulically driven pumping in parallel	98	1. Brine and feed are separated by [illegible]iston to ens[illegible]m mixing 2. For a piston designed for minim[illegible] drag [illegible]sfer of energy is essentially 100%	1. High capital cost 2. Booster pump is needed 3. Mixing, lubrication, overflush, high pressure differential, low pressure differential
PX	Hydraulically driven pumping in parallel	98	1. Core built of ceramic [illegible]ted to b[illegible]deal material for its toughness, corrosion [illegible] and di[illegible]sional stability withstanding the [illegible]hest s[illegible]e enviro[illegible]ents. Unlike turbines no transformati[illegible] losses [illegible] a PX device 2. Stable [illegible]ency ov[illegible]ide range of recoveries lack of traditi[illegible]eals and bea[illegible]	1. High capital cost 2. Booster pump is needed 3. Complexity of design, operation and maintenance 4. Mixing, lubrication, overflush, high pressure differential, low pressure differential

increase in membrane feed salinity [illegible] quantified with [illegible] following expression:

$$mixing = \frac{(membrane\ feed\ salinity - [illegible]m\ feed[illegible]ater\ salinity)}{sy[illegible]edwa[illegible]sali[illegible]y} \quad (5)$$

Mixing is a func[illegible] of th[illegible] membrane recovery rate and the mixing characteristic[illegible] [illegible] ERD. Mixing can be computed by mass balanc[illegible]r approximated with the following empirical Eq. (2):

$$\text{Mixing} \approx \text{membrane recovery} \times 0.0615 \quad (6)$$

Finally, the following two equations are driven to quantify the energy consumed in the high-pressure portion of the SWRO process, (this typically accounts for most of the energy consumed in the process). Where, the energy required in pre- and post-treatment is substantially independent of ERD type [6]

$$Energy = \frac{Q_{HP} \cdot P_{HP} - Q_R \cdot P_R \cdot \eta_T \cdot \eta_{HP}}{\eta_{HP} \cdot \eta_{HPM}} \quad (7)$$

where Q_{HP} is the high-pressure pump flow rate, P_{HP} is the high-pressure pump differential pressure, η_{HP} is the high-pressure pump efficiency, Q_R is the turbine flow rate, P_R is the turbine differential pressure, η_T is the turbine efficiency and η_{HPM} is the high-pressure pump motor efficiency. Pelton turbines discharge at atmospheric pressure so P_R is, effectively, the membrane reject

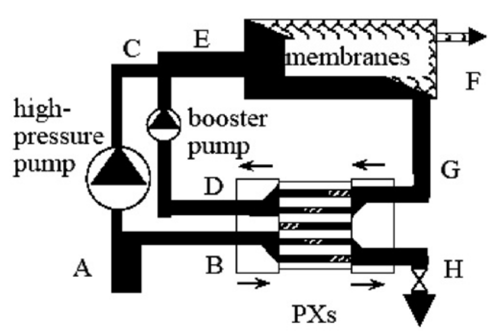

Fig. D1. SWRO system with PX.

pressure. Q_{CP} is the circulation pump flow rate, P_{CP} is the circulation pump pressure and η_{CP} is the circulation pump efficiency, η_{CPM} is the circulation pump motor efficiency and the rest of the variables were defined above. It should be noted that the efficiency or performance of the isobaric ERD is not directly included in the energy consumption equation, rather it appears implicitly as a reduction in the high-pressure pump flow rate, Q_{HP}

$$Energy = \frac{Q_{HP} \times P_{HP}}{\eta_{HP} \times \eta_{HPM}} + \frac{Q_{CP} \times P_{CP}}{\eta_{CP} \times \eta_{CPM}} \quad (8)$$

Example calculations: Hypothetical SWRO system parameters were borrowed from a recently published paper by Irving Moch et al. Three SWRO system examples are differentiated by their permeate flow rate in cubic meters per day (m^3/d) and feedwater salinity in parts per million (ppm):

- *Ex.* 1: 4273 m^3/day, 37,000 ppm.
- *Ex.* 2: 13,435 m^3/day, 44,000 ppm.
- *Ex.* 3: 25,091 m^3/day, 34,000 ppm.

A membrane recovery ratio of 40%, 24 °C water temperature and 2.8 bar supply pressure were assumed. Pump and motor efficiencies from the best available models were used. A conventional membrane projection program was used to estimate membrane feed pressures as a function of feed salinity. Other assumptions were consistent with those made in the referenced publication.

A summary of PX system operating conditions and specific energy consumption rates for the three examples are presented in Table D1.

The specific energy values presented in Table 1 are significantly lower than published values for comparable systems operating with centrifugal energy recovery devices.

RO product cost calculations:

The RO cost data include the following:

Direct capital cost (DC)=$98 × 10^6

Membrane purchase cost (@60%DC)=$58.8 × 10^6

Membrane annual replacement cost (@10% of membrane purchase cost)=A_4 $58.8 × 10^5

Plant capacity (m)=94,625 m^3/d

Electric cost (c)=$0.04/$m^3$

Specific consumption of electric power (w)=5 kW h/m^3

Specific cost of operating labor (L)=$0.05/$m^3$

Specific chemicals cost (k)=$0.033/$m^3$

The calculations proceed as follows:

1. Calculate the amortization factor

$$a=\frac{i(1+i)^n}{(1+i)^n-1}=\frac{0.05(1+0.05)^{30}}{(1+0.05)^{30}-1}=[illegible]065[illegible]\ \mathrm{yr}^{-1}$$

2. Calculate the annual fixe[illegible]arges

$$A_1=(a)(\mathrm{DC})=0.065051\left(98\ [illegible]\right)=\$[illegible]75\,041/\mathrm{yr}$$

3. Calculate the [illegible]ual el[illegible]ric power cost

$$A_2=(c)(w)(f)(m)([illegible]=(0.04)([illegible])(0.9)(94{,}625)(365)=\$6216863/\mathrm{yr}$$

4. Calculate the annual chemicals cost

$$A_3=(k)(f)(m)(365)=(0.033)(0.9)(94{,}625)(365)=\$l{,}039{,}129/\mathrm{yr}$$

Table D1
SWRO system energy calculations results.

	Q_{HP} (m^3/h)	P_{HP} (bar)	Q_{BP} (m^3/h)	P_{BPI} (bar)	η_{HP} (%)	η_{BP} (%)	η_M (%)	SE (kW h/m^3)	η_{PX} (%)
Ex.1	**184**	**63.1**	**261**	**60.7**	**80**	**78**	**95**	**2.41**	**95.3**
Ex.2	**582**	**76.3**	**818**	**73.5**	**85**	**83**	**95**	**2.77**	**95.2**
Ex.3	**1080**	**57.8**	**1534**	**55.3**	**90**	**88**	**96**	**1.95**	**94.8**

Table D2
Summary of cost calculation results, explained above.

	$	$/$m^3$	$/($m^3$/day)
Fixed charges	6,35,041	0.205	67.4
Electric power	6,216,863	0.200	65.7
Chemicals	1,039,129	0.033	11
Membrane replacement	5,880,000	0.189	62.1
Operating labor	1,554,216	0.050	16.4
Total	21,065,248	0.678	222.6

5. Calculate the annual membrane replacement cost

$$A_4=\$5{,}880{,}000/\mathrm{yr}$$

6. Calculate the annual labor co[illegible]

$$A5=(i)(f)(m)(365)=(0.05)[illegible](94{,}625)[illegible]5)=\$1554{,}216/\mathrm{yr}$$

7. Calculate total ann[illegible] cost

$$A_t=A_1+A_2+A_3[illegible]+A[illegible]$$
$$=6{,}375{,}0[illegible]+6{,}[illegible]63+1[illegible]9{,}129+5{,}880{,}000$$
$$+1{,}554[illegible]6=\$21{,}0[illegible]24[illegible]\mathrm{yr}$$

8. Calculate unit p[illegible]uct cost per m^3

$$[illegible]=A_t/((f)(m)(365))=(21{,}065{,}248)/((0.9)(365)(94{,}625))$$
$$=\$0.67[illegible]m^3$$

9. C[illegible]nit product cost per m^3/d

$$A[illegible]=A_t/((f)(m)(365))=(21{,}065{,}248)/(94{,}625)=\$223.1/(m^3/d)$$

The summary of annual cost data of the RO process is given in Table D2.

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